Exchange Interactions in Magnetic Semiconductors and their Nanostructures

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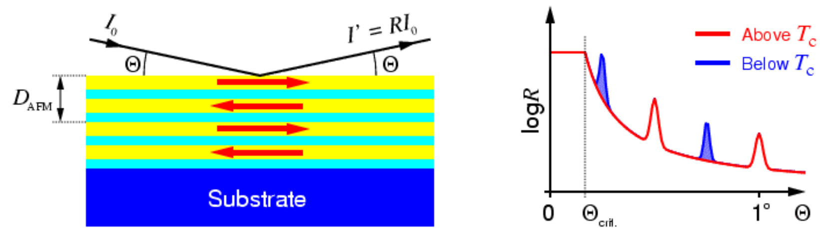
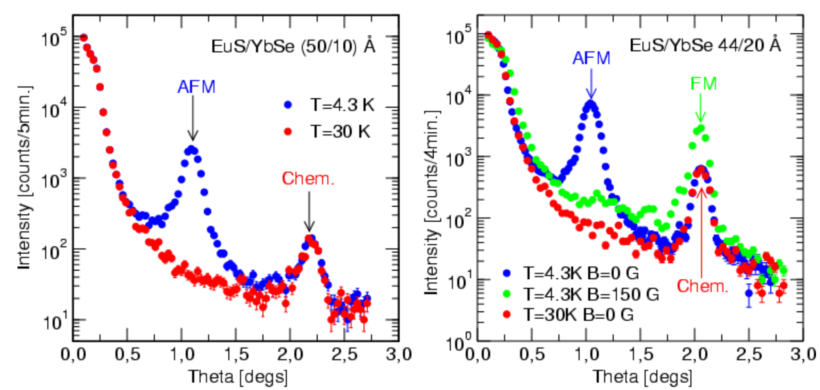
Exchange Interactions (EIs) between magnetic atoms are responsible for most magnetic phenomena seen seen in solids. It is well understood that in magnetic *metals* the EIs are mediated by conduction electrons. However, due to the emergence of a novel R&D field called *spintronics,* much attention of researchers is currently focused on magnetic *semiconductors.* Certain questions concerning the mechanisms of EIs in these materials are not yet entirely clear. We used inelastic neutron scattering to obtain first accurate quantitative information about the EIs in a ferromagnetic (FM) semiconductor mediated not by electrons, but by *holes* (Phys. Rev. Lett. **91**, 087206 (2003)). Using the technique of neutron reflectometry, we investigated superlattices (SLs) consisting of alternating layers of FM and nonmagnetic wide-gap materials, which are of potential use as novel magnetic field sensors. Our results prove that the adjacent FM layers are magnetized in opposite directions, and the EIs responsible for that are mediated by *valence electrons.*

Neutron Reflectivity from Ferromagnetic/Nonmagnetic SLs
Alternating Magnetization Direction in Consecutive Layers



Scheme explaining that for "antiferromagnetic" (alternating) layer magnetization, new peaks (blue) appear in the reflectivity spectrum for T below the Curie temperature (T_C), in-between the "structural" peaks (red) seen for T above T_C .



Spectra from a EuSe/YbSe SL specimens. The blue peaks seen for $T< T_C$ indicate alternating layer magnetization.

Spintronics is a novel electronics in which not only the current magnitude, but also its *spin state* is controlled. First-generation spintronics devices -- metallic magnetic field sensors utilizing the effect known as Giant Magneto-Resistance (GMR) -- are already being used in reading heads in computer disc memories. The current goal in spintronics R&D efforts is to develop devices that can be directly integrated into semiconductor chips. The progress in this area hinges critically on finding new synthetic semiconducting room-temperature ferromagnets. Much attention is currently focused on semiconducting alloys in which ferromagnetism arises from an interaction mechanism mediated by *holes.* Good theoretical understanding of that process is a matter of considerable importance. Certain controversial issues that have emerged in theoretical studies can be resolved only through accurate experimental measurements of the interactions in "prototypical" alloys. In order to provide such information, we have determined the strength of hole-induced ferromagnetic interactions between Mn ions in Zn(Mn)Te using the technique of inelastic neutron scattering (H.Kepa *et al.,*Phys. Rev. Lett. **91**, 087206 (2003)). Other systems investigated by us are binary superlattices composed of alternating layers of ferromagnetic (FM) and nonmagnetic semiconducting materials (EuS and PbS or YbSe, respectively). An interesting question in the context of spintronics studies is to determine how the FM layers interact across the intervening non-magnetic semiconducting "spacers". Our neutron reflectometry studies provide conclusive evidence that the interactions are conveyed not by mobile carriers, but by *valence electrons.*

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Education:

Two undergraduates (Joerg Rottmann, and Doug Fettig) and three graduate students (Silas Scott, Zach Wiren, and Tim Steckmann) contributed to this work. Joerg was an exchange student from Germany, and he will continue as a graduate student in Heidelberg, Germany. Doug will start his junior year this fall, and he intends to continue working with the PI. Silas defended his Ph.D. in October 2003 and is now working for Intel. Tim received his M.Sc. Degree in August 2004. In the year 2004/05 Zach will work on his Ph.D. project as a Research Assistant supported by the present award.

Societal Impact:

This project, focused on increasing our understanding of certain phenomena seen in novel magnetic semiconductors, is a part of a broad worldwide R&D effort, the objective of which is to develop practical semiconductor-based spintronics devices. Such devices may have a profound impact on future communication and computer technologies.